AFRL-SN-WP-TP-2002-106

CONTEXT AND QUASI-INVARIANTS IN AUTOMATIC TARGET RECOGNITION (ATR) WITH SYNTHETIC APERTURE RADAR (SAR) IMAGERY

Thomas O. Binford
By-Her Wang
Tod S. Levitt

JUNE 2002

Approved for public release; distribution is unlimited.

SENSORS DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7318

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
June 2002	Journal Article	07/01/1993 – 12/31/1997

4. TITLE AND SUBTITLE
CONTEXT AND QUASI-INVARIANTS IN AUTOMATIC TARGET RECOGNITION (ATR) WITH SYNTHETIC APERTURE RADAR (SAR) IMAGERY

5a. CONTRACT NUMBER
F33615-93-1-1281

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
63226E

6. AUTHOR(S)
Thomas O. Binford
By-Her Wang
Tod S. Levitt

5d. PROJECT NUMBER
A374

5e. TASK NUMBER
R1

5f. WORK UNIT NUMBER
A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Stanford University
Robotics Laboratory
Computer Science Department
Stanford, CA 94305

8. PERFORMING ORGANIZATION REPORT NUMBER
169M005-2100MA439

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Sensors Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7318

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/SNAT

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-SN-WP-TP-2002-106

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Technical paper published in *DARPA Image Understanding Workshop Proceedings*, Vol. II, pp. 1031-1039, May 1997.

14. ABSTRACT
This analysis of XPatch synthesized SAR images shows promising results on existence of persistent scatterers and their measurement in XPatch imagery. Preliminary results based on persistent scatterers and a generic vehicle model demonstrate estimation of vehicle orientation to about 3 degrees, length between wheels to about 30 cm, and estimating number of wheels, without knowledge of vehicle class or pose. Planned research will investigate recognition using generic target and clutter models in analysis of a stable, useful subset of radar images. Research will include quantitative characterization of persistent scatterers and stable relations, an end-to-end recognition test, and investigation of supporting technology for MSTAR. The paradigm offers a genuine methodology to cope with articulation and obscuration.

15. SUBJECT TERMS
automatic target recognition, ATR, quasi-invariants, synthetic aperture radar, SAR

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Vincent Velten
Unclassified	Unclassified	Unclassified	SAR	10	19b. TELEPHONE NUMBER *(Include Area Code)* (937) 255-1115 x4388

HES&S 31-15093-1

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Context and Quasi-Invariants in ATR with SAR Imagery

Thomas O. Binford, By-Her Wang, and Tod S. Levitt *

Robotics Laboratory, Computer Science Department
Stanford University, Stanford, CA 94305
http://robotics.stanford.edu/groups/reality/binford.html

Abstract

This analysis of XPatch synthesized SAR images shows promising results on existence of persistent scatterers and their measurement in XPatch imagery. Preliminary results based on persistent scatterers and a generic vehicle model demonstrate estimation of vehicle orientation to about 3 degrees, length between wheels to about 30 cm, and estimating number of wheels, without knowledge of vehicle class or pose. Planned research will investigate recognition using generic target and clutter models in analysis of a stable, useful subset of radar images. Research will include quantitative characterization of persistent scatterers and stable relations, an end-to-end recognition test, and investigation of supporting technology for MSTAR. The paradigm offers a genuine methodology to cope with articulation and obscuration.

1 Introduction

SAR imagery is known to vary rapidly with target angle. Scatterers appear and disappear over a few degrees. The resultant image variability makes ATR template matching computationally complex, requiring search for match over a relatively dense set of angles. That image variability also lessens the discrimination power of template matching in ATR, because data images cannot be guaranteed to match exactly. Matching errors tend to introduce biases in matching; matching algorithms must relax matching constraints. Existing systems work reasonably for unarticulated, unobstructed targets, *e.g.* MSTAR and [Ikeuchi 96; Novak 94; Novak 95; Novak 96]. However, results degrade with obscuration and articulation.

Research leading to this project was intended to investigate whether a stable, useful subset of radar images could be found, i.e. to investigate whether persistent scatterers exist, enough scatterers sufficiently persistent that indexing could be done initially with persistent scatterers, to characterize their behavior in a preliminary way, and to demonstrate that scatterer peaks could be estimated accurately to represent target signals in MSTAR or in an intended matching algorithm.

We were motivated by analysis of scattering of target components to ask whether stable scatterers exist. A component scattering model was not regarded as plausible in 1991. In turntable experiments, [Dudgeon 94] found evidence for persistent scatterers, a minimum of about 10 at any angle, persistent for a minimum of 20 degrees, with no disappearance of more than one degree. Subsequently, we found persistent scatterers in XPatch data. A better analytic understanding was since derived for persistent scatterers and for a generic component scattering model.

An analysis based on partial matching of persistent features to generic vehicle models was proposed as a solution to recognition with obscuration and articulation. Generic models with partial matching is also a methodology for hypothesis generation without exhaustive enumeration of targets and poses. Lessening variability by choosing persistent scatterers and stable relations might possibly compensate in part for the loss of unavoidable loss of discriminability with obscuration and articulation.

The objective of this project is to develop target recognition based on persistent scatterers and stable relations in the support of the MSTAR paradigm for ATR and in development of a new recognition system. The following subgoals lie along the path toward that goal: to characterize persistent scatterers

*This research was supported by a contract from the Air Force, F33615-93-1-1281 through WPAFB from ARPA ASTO "Multi-Sensor ATR: Quasi-Invariants and High Accuracy Measurements in Bayesian Inference" and "Context and Quasi-Invariants in ATR with SAR Imagery".

further; to characterize stable relations among persistent scatterers; to investigate non-persistent scatterers and incorporate matching them in a matching scheme; to develop a generic image model and generic target model; to derive and implement a recognition algorithm in a Bayesian network [Binford *et. al.* 87], based on generic image and target models to estimate angle and dimensions of vehicles without enumerating vehicle class and pose.

At the same time, context is widely regarded as an effective way to eliminate large classes of clutter from fixed targets and civilian vehicles [Levitt 95]. This research will investigate context-enhanced discrimination of targets vs natural and cultural clutter based on correspondence between context from available databases (*e.g.* DMIF or HUB) and extended structures registered from imagery [Oliver 90; Posner 93; Wellman 93]. Progress in using context will come from improved discrimination using structures found from texture analysis and from buildings discriminated from analysis of leading edges in their radar image.

2 Toward an Effective Methodology

Some questions need to be answered concerning effectiveness of this methodology. 1) Is there a useful, stable subset of a SAR image, enough persistent scatterers to constrain target hypotheses, sufficiently persistent to implement a hierarchical indexing scheme proposed in this component-based, body-centered recognition paradigm? 2) Are there stable relations among persistent scatterers that enable partial matching that is computationally affordable? Among partial matching algorithms are both computationally effective and computationally expensive algorithms. 3) Can features be extracted from persistent scatterers accurately enough over a broad range of target orientations with enough independence from interference among scatterers to enable stable estimation of scatterer locations and stable estimation of relations among them to enable estimating vehicle orientation and dimensions without knowing vehicle class or orientation. 4) Can a generic vehicle model be formulated that gives a basis for predicting automatically which stable relations will exist and be useful in a broad range of images.

We show preliminary results for XPatch data for three vehicles. Using synthesized data provides data over a range of controlled situations essential to developing a sound algorithm basis, before development on real data. Ikeuchi at CMU provided the XPatch data. In Figure 1, at the top is a low quality optical image of a BTR60. Below it are 6 SAR images from XPatch at a range of angles: 6, 12, 18 degrees, then below, 30, 36, 42 degrees. Note that the SAR images are defocussed in the range direction; presumably they could be focussed better by a choice of XPatch parameters. At the bottom are intensity profiles along the leading edge of the target at angles of 31, 37, and 43 degrees and 69, 75, and 81 degrees. We see four peaks with nearly constant amplitude (to 15%). Note that the peaks persist from 6 degrees to 174 degrees, nearly the whole target angle range. The BTR60 has four wheels with wheel spacing consistent with the good measurements available from peak detection. Wheel spacings provide a geometric invariant (or several) and several geometric quasi-invariants. Peak amplitudes provide photometric quasi-invariants independent of photometric calibration of the image.

Figure 2 shows evidence of persistent scatterers over the whole vehicle. In the upper left are peak scatterers for the BTR60, extracted by our peak detection algorithms from XPatch images over angles from 45 to 135 degrees. Results are similar over nearly 0 to 180 degrees. Peaks extracted from XPatch images at 1 degree intervals for constant slant angle are rotated to zero degrees azimuth and superimposed. We see four clear clusters on the leading edge and eight or nine more clusters interior on the vehicle, along the top. On the middle right, the four peaks were isolated using their statistical distribution. In the lower left, the four peaks are shown in a 3D plot intended to demonstrate in an intuitive and semi-quantitative way the level of persistence of the scatterers. The plot shows (x,y) position as a function of azimuth angle at angles from 45 to 135 degrees. If we look along the vehicle leading edge (x), we see that the peaks are well-separated, with few dropouts.

Existence of stable relations seem to be born out by measurements of ratios of wheel spacings over large ranges of angles. There is also strong analytic reasoning in support of geometric invariants and quasi-invariants. Subsequent detailed SAR image analysis may strengthen and refine this expectation. Much more analysis will be made of similar data using XPatch backtrace facilities to determine where the true scatterers are, to quantify variability of individual scatterers for incorporation into estimation and decision algorithms, and to serve as ground truth for peak estimation and feature detection. Non-persistent scatterers and the ratio of persistent to non-persistent will be studied. These investigations will be carried out in collaboration with Vince Velten from Wright-Patterson AFB and Dr. Eamon Barret and Dr. Paul Payton from Lockheed-Martin.

Figure 3 shows preliminary steps in target recognition. In the upper left is an XPatch image of the BTR60 at 45 degrees. The lower left shows the Delaunay triangulation of peaks detected from the XPatch image in the target cluster. In the upper right are peaks detected in the image, with peaks on the longer leading edge marked with a surrounding circle; peaks on the shorter leading edge are marked

with a cross. The leading edge perpendicular pair is shown by solid lines. In the lower right, candidate peaks along the leading edge were selected for intensity from the generic vehicle model to generate candidates for wheels. Estimated leading edge orientation, length, width, and distances between wheels are shown.

We are developing an algorithm for estimating leading edges of targets, insensitive to points not on the leading edge. This is a problem for which least-squares estimation is ill-suited. Least squares weights most heavily points that are furthest away. A non least-squares method was developed, essentially that used in linking in the Binford-Horn edge operator. That operator will be used in computing leading edges of buildings to discriminate buildings and other fixed clutter from targets.

Figure 4 shows estimation of azimuth angles over a broad range of angles in XPatch data for three targets, BTR60, KTANK, and BMP. These estimates cover a range from 10 to 170 degrees; above we saw that the range could be extended a little further, but it cannot be extended below about 5 degrees. [Dudgeon 94] observed that zero degrees and ninety degrees were special views. Those views showed up in our experiments and for physical reasons, in our generic vehicle model.

Over this wide range of angles, the standard deviations for vehicle azimuth angles were 4.0, 2.3, and 3.7 degrees. We believe that the measurement will improve because we are still developing the algorithm. It still makes mistakes in including interior, non leading edge points that bias the result. Standard deviations are strongly affected by these mistakes, i.e. wild points.

Figure 5 shows persistence for KTANK similar to Figure 2 for the BTR60. In Figure 5, top, peaks from views at 1 degree intervals from 0 to 180 degrees were rotated into the 0 degree coordinate frame and superimposed. At the bottom are peaks from the longer leading edge Vive peaks appear more irregular than in the BTR60 images. Again, the peaks persist over nearly the whole angle range.

Similar results were obtained for the BMP. They are omitted to cut space and to avoid detail.

3 Observations

Persistent scatterers have been demonstrated in real SAR from turntable data [Dudgeon 94], in XPatch synthesized SAR, and predicted in analysis. At this early stage, the apparent ratio of persistent to non-persistent scatterers is more favorable than expected. There appear to be about a dozen persistent scatterers on vehicles like the three shown here. Their persistence appears over a broader range of angles than initially expected but now appears to follow from good reasons.

Are there enough scatterers? There appear to be about 12 persistent scatterers typical for these targets. If only 30% of them were obscured, the remainder seem sufficient. In SAR, two scatterers along the leading edge provides a measured constraint; three scatterers are over-constrained. Relative to a leading edge estimate, an additional point off the leading edge is another constraint on matching. With only three points, there are two constraints.

A next step is incorporating points interior to the leading edge, again exploiting the generic model. Some of that can still be done at a generic level for vehicles.

One foot resolution appears to be a magic resolution at which useful detail becomes apparent for vehicles the size of the military vehicles used in these XPatch studies, about 8 meters, 27 feet. Although many pixels cover these vehicles' images, it is the size of scatterers that matters here. There are few pixels on wheels, turrets, and other observable structures. Our estimation methods seem to be on the borderline of resolving the wheels on the vehicles. Making effective use of available image resolution is extemely important.

It seems that improvements in the peak detection provides strong leverage for the problem. I.e. resolving the wheels in all cases on the leading edge would contribute substantially to classifying vehicles. The current peak detection was conceived for isolated peaks; it appears very useful in terrain and vegetation. On targets, peaks overlap, affecting peak detection. Rather than implement our understanding of a solution to the overlapping peak roblem, we have chosen thus far to push on to a broader, birds-eye view of the issues. We are considering improvements in image and in feature detection in the raw SAR phase history data before image formation or exploiting those advances of others in superresolution [Cabrera 94; Mann 92; Odendaal 94].

In fact, measurement of dimensions seems to be relatively accurate. The distance between wheels has a standard deviation of 10 inches. These dimensions go a long way toward constraining vehicle class.

4 Conclusions

These preliminary results appear to warrant further investigation. Persistent scatterers have been demonstrated in real and synthesized SAR experiments; they are expected to exist for good reasons. At this early stage, persistence appears over nearly the whole angle range, again for good reasons. A suf-

ficient number of persistent scatterers appear that it seems promising to recognition. Peak detection seems adequate for initial investigation. further accuracy refinement may be necessary to exploit available imagery. A generic vehicle model has proved surprisingly powerful.

5 References

[Benitz 94] G.R.Benitz, "Adaptive High-Definition Imaging"; *SPIE* Vol 2230, pp 106-119, 1994.

[Binford 87] T.O.Binford, *et. al.*, "Bayesian Inference in Model-Based Machine Vision"; *Proc Workshop on Uncertainty in AI*, AAAI87, 1987.

[Cabrera 94] S.D.Cabrera, *et. al.*, "Application of One-Dimensional Adaptive Extrapolation to Improve Resolution in Range-Doppler Imaging"; *SPIE* Vol 2230, pp 135-145, 1994.

[Dudgeon 94] D.E.Dudgeon, *et. al.*, "Use of persistent scatterers for model-based recognition"; *SPIE* Vol 2230, pp 356-368, 1994.

[Haag 91] N.N.Haag, *et. al.*, "Invariant Relationships in Side-Looking Synthetic Aperture Imagery"; *Photgrammetric Engineering and Remote Sensing*, V 57 pp 927-931, 1991.

[Ikeuchi 96] K.Ikeuchi, *et. al.*, "Invariant Histograms and Deformable Template Matching for SAR Target Recognition"; *Proc IEEE CVPR*, pp 100-105, 1996.

[Jane 84] Foss, Christopher F. "Jane's Light Tanks and Armoured Cars"; 1984.

[Levitt 95] Levitt, T.S., *et. al.*,"Bayesian Inference-Based Fusion of Radar Imagery, Military Forces and Tactical Terrain Models in the Image Exploitation System/Balanced Technology Initiative", *Intl. J. of Human-Computer Studies*, No. 42, 1995.

[Mann 92] J.Mann and R.Hummel, "Synthetic Aperture Radar without Fourier Transforms"; Courant Institute, 1992.

[Moulin 93] P.Moulin, "A Wavelet Regularization Method for Diffuse Radar-Target Imaging and Speckle-Noise Reduction"; *Journal of Mathematical Imaging and Vision*, 3, 123-134, 1993.

[Novak 94] L.M.Novak and G.J.Owirka, "Radar Target Identification Using an Eigen-Image Approach"; *IEEE National Radar Conference*, Atlanta, GA, 1994.

[Novak 95] L.M.Novak, *et. al.*, "Effects of Polarization and Resolution on the Performance of a SAR Automatic Target Recognition System"; *Lincoln Laboratory Journal*, Vol 8, pp 49-68, 1995.

[Novak 96] L.M.Novak, *et. al.*, "ATR Performance Using Enhanced Resolution ATR"; *SPIE Conf on Algorithms for Synthetic Aperture Radar Imagery III*, 1996.

[Odendaal 94] J.W.Odendaal, *et. al.*, "Two-Dimensional Super resoltuion Radar Using the MUSIC Algorithm"; *IEEE Transactions on Antennas and Propagation*, V 42, pp 1386-1391, 1994.

[Oliver 90] C.J.Oliver, "Clutter Classification based on a correlated noise model"; *Inverse Problems*, 6, PP 77-89, 1990.

[Owirka 94] G.J.Owirka and L.M.Novak, "A New SAR ATR Algorithm Suite"; *Conf on Algorithms for Synthetic Aperture Radar*, 1994.

[Posner 93] F.L.Posner, "Texture and Speckle in High Resolution Synthetic Aperture Radar Clutter"; *IEEE Trans on Geoscience and Remote Sensing*, V 31, pp 192-203, 1993.

[Wang 96] B. Wang and T.O. Binford, "Generic, Model-based Estimation and Detection of Peaks in Image Surfaces", *Proceedings of Image Understanding Workshop*, Vol. 2, pp.913-922, Feb. 1996.

[Wellman93] R. J. Wellman, *et. al.*, "Radar Cross Sections of Ground Clutter at 95 GHz for Summer and Fall Conditions"; AGARD meeting on Atmospheric Propagation Effects through Natural and Man-Made Obscurants for Visible to MM-Wae Radiation, 1993.